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Modelling a probabilistic safety management system for the Eastern-Scheldt storm-surge barrier, the basin and the surrounding dikes

A. Willems & P.B. Webbers
Ministry of Transport, Public Works and Water Management. Department of Risk Analysis, Netherlands

ABSTRACT: The Dutch government wants to have a computer model that calculates the annual probability of flooding the area around the Eastern-Scheldt. This model should also be able to determine the impact of maintenance and control management of the Eastern-Scheldt storm-surge barrier and dikes surrounding the basin. In this paper an approach is presented to obtain a model of this so-called safety management system using the design tool IDEF0. The model consists of a deterministic description of the system and will be translated into annual probabilities using Monte Carlo (MC) simulation.

1 INTRODUCTION

1.1 *Background*

The Eastern-Scheldt storm-surge barrier was built from 1979 to 1986 to protect the south-west of the Netherlands against flooding. It consists of 62 moveable steel gates which only close in case of (expected) high water levels.

Together with the dike rings surrounding the Eastern-Scheldt, the second flood defence line, the Eastern-Scheldt storm-surge barrier forms the defence system that protects the hinterland against flooding. Of course, this flood defence system must be very reliable to guarantee an acceptable safety level of the hinterland. The Dutch government accepts a maximum annual probability of flooding of $2.5 \cdot 10^{-5}$ for the storm-surge barrier and dikes surrounding the Eastern-Scheldt, and a maximum annual probability of flooding of $2.5 \cdot 10^{-4}$ for the compartment dams. The reliability of the storm-surge barrier and dikes must be determined at least once every five years to see if they still meet these safety requirements.

In case of an oncoming storm the expected water levels on the Eastern-Scheldt are calculated by a water movement computer model. If the expected water level exceeds NAP[1] +3.0 m the model will advise to close all 62 gates. For the Eastern-Scheldt storm-surge barrier the so-called "changing strategy" is in use on environmental considerations. This strategy implies specific moments of closing and opening of the barrier. These moments lead to the adjustment of an average water level on the Eastern-Scheldt changing from NAP +1.0 m to NAP +2.0 m to NAP +1.0 m et cetera.

Figure 1. The Eastern-Scheldt storm-surge barrier.

It is important to emphasise that the moments of closing and opening of the barrier, given by the model, are only meant as an advise and should be evaluated and executed by humans. This is in contrast with the Dutch Maeslant storm-surge barrier near Rotterdam, which closes and opens fully automatically. There is one exception however: in case the water level near the Eastern-Scheldt storm-surge barrier *actually* reaches the level of NAP +3.0 m all 62 gates close automatically. This is called the "emergency closure".

Both the manual closure and the backup emergency closure are tested twice a year. Since 1986 the barrier has been closed twenty times for safety reasons.

[1] Dutch reference plane.

Due to sea level rise, settlement of bottom level and deterioration of materials, the flood defence system must be maintained every year in order to keep up to the required reliability levels. Nowadays, the regular checks on reliability of the storm-surge barrier and the dikes are done separately. Good insight in the interactions between the reliability of both structure types in the total system is preferable. Since maintenance of both barrier and dikes is expensive, the economical benefit of such insight could be significant. For example, changing the closing strategy or maintenance of the storm-surge barrier could possibly allow no heightening of the dikes for many years.

1.2 *Problem*

From an economical point of view optimisation of maintenance for the whole flood defence system is more profitable than doing this for the individual parts separately. To make this optimisation possible we should be able to calculate the over-all reliability of the flood defence system and determine its impact on maintenance costs.

The Dutch government wants to have a computer model, which can automatically calculate the reliability of the flood defence system in probabilistic terms. This model must be compatible with both existing and future tests of dikes. Of course, it must be able to determine the effects of maintenance on the reliability of the flood defence system. An additional preferable feature is the determination of effects on the reliability due to changes in the closure strategy of the barrier. In other words, it would like to have a computerised safety management system (SMS).

One of the difficult matters is the time-dependency of the system in combination with the uncertainty of the water movements in the Eastern-Scheldt during a storm. For example, failure of the storm-surge barrier does not necessarily have to lead to flooding of the hinterland. This depends, among others, on the type of storm, the local water depths, the strength of the dikes and the capacity of the Eastern-Scheldt basin. Since this capacity is not exactly known, it is not only difficult to predict if flooding takes place, but also when this takes place.

Additional difficulty is the large amount of different storm types, together with the number of failure modes of the storm-surge barrier, for which the behaviour of water in the Eastern-Scheldt should be modelled. Furthermore, since only a very small number of these storms may lead to flooding of the hinterland, the SMS model should be able to deal with small probabilities.

It is therefore an interesting challenge to develop a computerised SMS which takes into account the interaction between the reliability of a storm-surge barrier and the reliability of the dikes lying behind the barrier. Especially since the same principle could be used for other storm-surge barriers, e.g. the Dutch Maeslant storm-surge barrier.

1.3 *Approach*

The first step in developing a computerised SMS is describing the system that has to be modelled. Another important aspect is the outcome of the model. It should obviously be a probabilistic measure of safety against flooding of the hinterland (the “safety level” of the system), but which measure should be taken?

Secondly, an overview of the state-of-the-art is necessary: which studies have been made related to this subject and which useful methods and models already exist?

Third step is to describe a relationship between the suitable methods to determine the reliability of the storm-surge barrier and the reliability of the dikes. In fact, all relevant relationships within the system should be described. For this purpose the so-called IDEF0 method is used. Consequently, the system is described in a deterministic way. The necessary translation to a probabilistic outcome will be accomplished by using a Monte Carlo (MC) simulation technique.

To limit the amount of work some simplifications are carried out in modelling this complex system. The IDEF0 description will be used to see the effect of each simplification on the over-all model.

At this stage the impact of maintenance of the storm-surge barrier and dikes on the safety level is not yet taken into account.

2 SAFETY MANAGEMENT SYSTEM

2.1 *System description*

The system that needs to be modelled incorporates the North Sea, the Eastern-Scheldt storm-surge barrier, the Eastern-Scheldt basin, the surrounding dike rings 26–31 and four so-called compartment dams, i.e. Grevelingendam, Philipsdam, Oesterdam and Zandkreekdam. The system boundaries are shown in figure 2.

Basically the relevant sequence of actions within the system can be described as follows:

- A storm occurs, which causes a water level rise near the Dutch coast;
- If necessary, the storm-surge barrier has to close all 62 gates;
- If the barrier works properly the amount of water in the Eastern-Scheldt basin will only increase due to leak through the barrier;
- The dikes surrounding the basin have to prevent flooding of the hinterland.

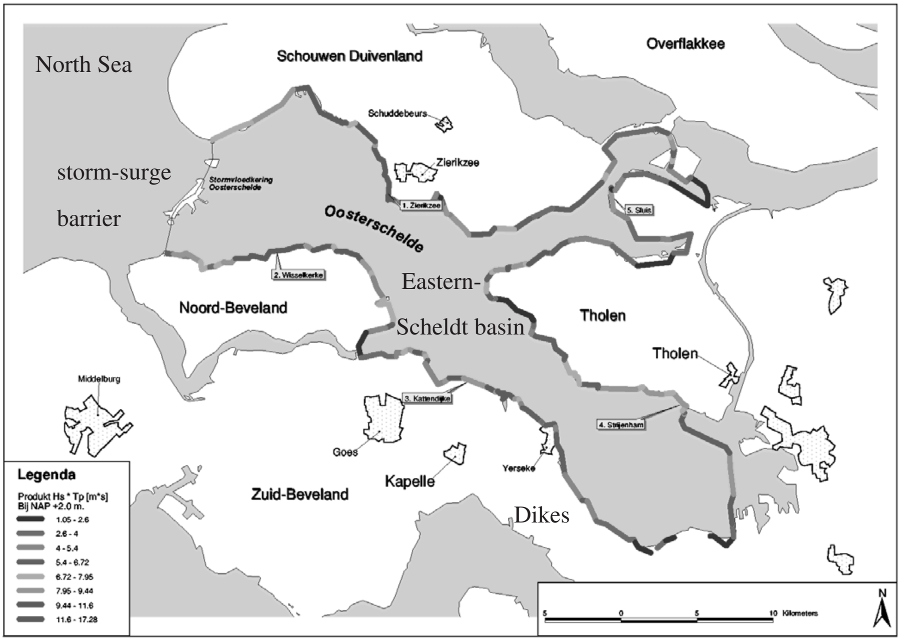

Figure 2. Boundaries of the safety system.

However, if the barrier fails to close all 62 gates an extra amount of water will leak through the barrier. This will lead to higher water levels in the basin. Consequently, the loads on most of the dikes increase and flooding of the hinterland will become more likely.

2.2 *Safety level*

The safety level of the SMS can be determined using system reliability techniques. In this context the safety level of the system is the same as its reliability, so we can define a so-called undesirable top event. Occurrence of this event can be seen as failure of the system. In this way the safety level of the SMS is equivalent to the probability of occurrence of the undesirable top event.

Looking at the required safety levels of the system used since the design of the storm-surge barrier we see some significant differences.

For the design of the barrier a maximum probability of failure of the system has been used of 10^{-7} per year (see Road and Hydraulic Engineering Division (1994)), while BARCON (1985) uses $2.5 \cdot 10^{-5}$ per year. The first requirement however corresponds with the undesirable top event of exceeding the average water level on the Eastern-Scheldt of NAP +4.3 m, while the second one corresponds with exceeding NAP +3.5 m. More recently, in 2000, the occurrence of a "flood disaster" has been used as an undesirable top event, and has been set to a maximum probability of 10^{-7} per year by the Directorate Zeeland (2000).

In defining the undesirable top event of the SMS structural failure of the storm-surge barrier is left out of consideration. For, however it may be an undesirable event, the safety system does not always fail if the storm-surge barrier (partly) fails. Failure of the SMS takes place not before at least one of the dikes surrounding the Eastern-Scheldt fails.

Therefore we use the undesirable top event "failure of one or more of the dike rings surrounding the Eastern-Scheldt basin". Since an important feature of the model will be the compatibility with both existing and future tests of dikes we mean by failure the occurrence of one of the failure modes summed up in Table 1.

2.3 *Existing studies, methods and models*

Since the design of the Eastern-Scheldt storm-surge barrier a long list of articles has been published. Studies have been made of the reliability of the storm-surge barrier (Van den Beukel & Kooman (1980), BARCON (1985)) and its control (Vereeke and Vroon 1999). Calculation methods to determine the reliability of the dikes are also known (TAW (1999), Vrouwenvelder et al. (1999)) To calculate the water levels on the Eastern-Scheldt several water

Table 1. Failure modes of a dike ring (Vrouwenvelder et al. 1999).

Overtopping
Wave overtopping
Slip circle inner slope
Slip circle outer slope
Erosion outer slope
Failure revetment en Erosion core
Macro instability outer slope
Macro instability inner slope
Micro instability inner slope
Burst of cover layer and Piping
Failure of constructions in the dike

movement models can be used, i.e. Simplic (used in BARCON (1985)) and Implic. The latter one has been used to determine the reliability of the dike revetments by calculating the water levels near the dikes for all possible storm types taking into account the probabilities of occurrence per storm (Stroeve F.M. 2000). Determination of the reliability of the dikes while taking into account a (partly or completely) failed storm-surge barrier is not common practice.

For practical reasons the focus is on using existing methods and models as much as possible during building of the SMS. This does not only reduce the amount of work; it will probably also reduce some of the "teething problems" that exist when developing a completely new model. On the other hand, the problem in using existing models and methods could be the lack of compatibility between them. To control this problem as much as possible we have made use of a design tool, called "IDEF0".

2.4 *IDEF0 method*

IDEF0 is a method designed to model the decisions, actions, and activities of an organisation or system. IDEF0 was derived from a well-established graphical language, the Structured Analysis and Design Technique (SADT). The United States Air Force commissioned the developers of SADT to develop a function modelling method for analysing and communicating the functional perspective of a system. As a communication tool, IDEF0 enhances domain expert involvement and consensus decision-making through simplified graphical devices. As an analysis tool, IDEF0 assists the model designer in identifying what functions are performed, what is needed to perform those functions, what the current system does right, and what the current system does wrong.

With IDEF0 we managed to combine the relevant aspects of the safety system into one integral model, such as the storm variables, the water movement, the failure of the storm-surge barrier and dikes and the occurrence of flooding.

3 SMS MODEL

3.1 *Monte Carlo simulation*

The annual probability of occurrence of the top event is the applied measure for the safety level of the hinterland. However, due to the complexity of the system this annual probability is not easily determined analytically. Therefore MC simulation will be used. As mentioned in the introduction, the model should be able to deal with small probabilities of occurrence. At this stage it is not clear to what extent the "traditional" MC will be sufficient for reliable calculations, or that we will have to use directional sampling techniques in order to reduce the number of MC runs.

3.2 *Monte Carlo model*

The over-all SMS model will be built as a MC model. The core of this MC model is a deterministic system describing a storm, the following water movements, the working of the storm surge barrier and whether or not the top event occurs.

The deterministic variables are drawn from probability density functions. By running the model a large number of times (for example 10,000 times) and checking every run whether or not the undesirable top event occurs, the percentage of runs in which this event does occur can be considered as the probability of occurrence of it. This can be done per year. The model will be set up in such a way that the impact of maintenance and management (for example the closing strategy) can easily be taken into account by changing the probability density functions of the state of the dikes, the state of the barrier or the moment of closing the barrier. Figure 3 shows the diagram of the SMS model.

3.3 *Deterministic system description*

In figure 3 the inner block represents the deterministic description of the system. This description has been made using IDEF0.

IDEF0 has the feature to describe the model on different levels of detail. Parts of the model can be zoomed in or zoomed out. The complete model has been described in IDEF0 schemes. In this paper we will only show two levels of detail, named A-0 and A0; see figures 4 and 5.

Figure 4 shows the highest level of the model. One block that represents the action "determine whether or not the undesirable top event takes place". The input consists of the water depths and capacity of the Eastern-Scheldt basin, together with the wind parameters and the astronomical tide. The output consists of not only the (non-) occurrence of the undesirable event, but also of the renewed water depths and

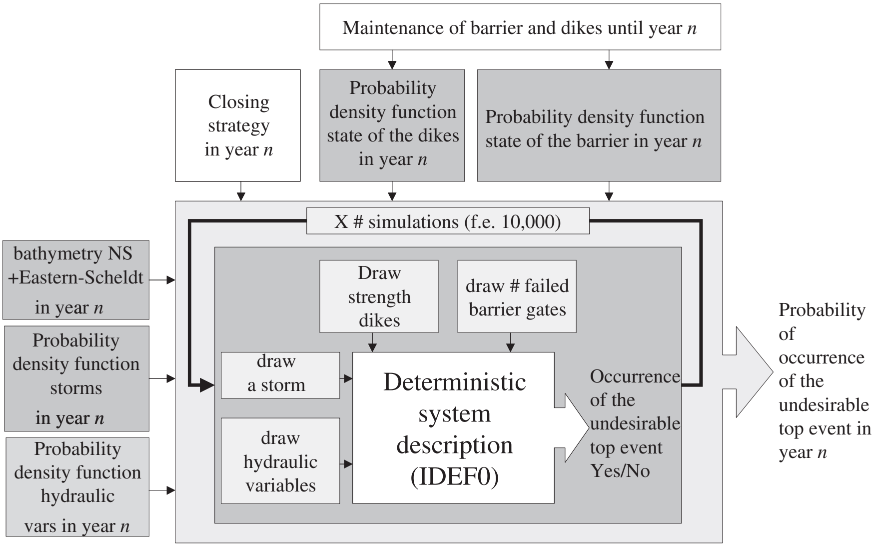

Figure 3. Diagram of the safety management model.

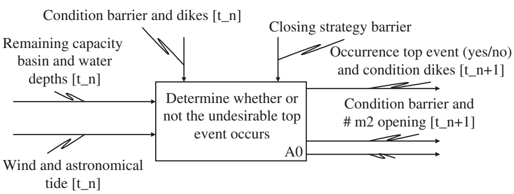

Figure 4. IDEF0 A-0 scheme of the SMS.

remaining capacity of the basin. This is where the time-dependency should be taken into account. The model represents the working of the system for a time interval $[t_n, t_{n+1}]$. During this interval water comes in from the North sea to the Eastern-Scheldt basin. The amount of water depends on the number of square meters opening in the storm-surge barrier, which – in turn – depends on the number of steel gates that failed to close plus the leak of the barrier. So, after a period of time the water depths and remaining capacity of the basin have changed and should be renewed and used again for modelling the time interval $[t_{n+1}, t_{n+2}]$.

The same thing goes for the state of the storm-surge barrier (the number of failed gates or other parts of the barrier) and the number of square meters opening. As stated above, this information is necessary for determining the amount of water coming from the North sea into the Eastern-Scheldt basin and should also be used again for the next time interval. This iteration continues until the end of the storm, or until the undesirable top event takes place.

The determination of the relevant hydraulic variables, e.g. H_s and T_p, the state of the storm-surge barrier, the remaining capacity of the basin and the water depths is being described in figure 5.

3.4 *Modelling water movements*

As mentioned in paragraph 2.3, apart from whether or not the undesirable top events occurs, the steps in figures 4 and 5 have been done before by Stroeve (2000). Using the computer model Implic for modelling the water movements in the Eastern-Scheldt, water levels near the dikes have been determined for 3600 different storm types. These calculations were made based on a fully closed barrier. Closing the barrier manually according to the computer advise as well as the emergency closure has been taken into account.

We can use these results for the situation in which all 62 gates of the barrier work properly. In case one or more of the gates fail to close the impact on the water levels is unknown. New (computer) calculations should be made for each combination of the number of failing gates and the type of storm. This would result in $3600 \cdot 62 = 223{,}200$ calculations. However, the moment of gate failure and the duration of failure are also important. The number of combinations will increase enormously if all these options are taken into account. Simplifications are necessary in order to reduce the amount of calculations.

3.5 *Simplifications*

In order to model the system properly and keep the number of required calculations within bounds,

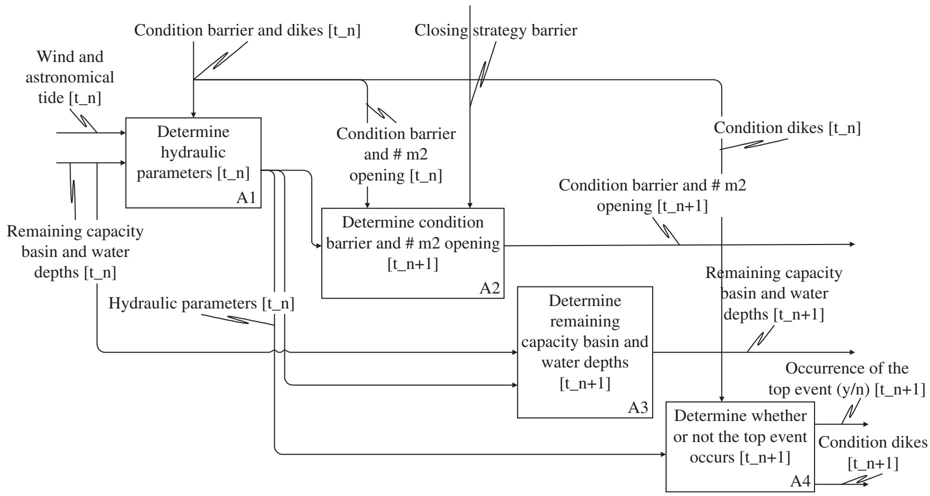

Figure 5. IDEF0 A0 scheme of the SMS.

simplifications have to be made. The most important ones are the following:

– Failure of the storm-surge barrier means failure of one or more of its gates. Other failure modes like structural failure will not be taken into account.
– Failure of the storm-surge barrier can only take place while closing or opening the barrier.
– The number of failing gates is categorised to 1, 2, 3, 4 and more than 4. The last one is set to all 62 gates.
– The duration of failing is categorised into less than 1 hour, 1 closing operation (about 12.5 hour) and longer than 1 day.
– The position of a failing gate is not relevant.

The moment of failure has not been simplified yet. First the idea was to consider each failure of a gate during a storm at the beginning of that storm, but that will probably be too conservative.

Another simplification was that failure to open the barrier would not be relevant for the flood risk However, since the changing strategy uses the opportunity to sluice water out of the Eastern-Scheldt basin into the North sea during the “low tide-period” in a storm, opening the barrier could be relevant to reduce the risk of flooding.

In one of the further steps these simplifications will be checked and determined by making some calculations using Implic.

4 PRELIMINARY RESULTS

At this stage the system description and model design have been made using IDEF0 schemes for all relevant levels of detail. We managed to use existing methods and models in a consistent over-all concept of the safety management system.

The IDEF0 method proved to be a powerful modelling tool. It is helpful in getting a complete overview of the system, especially the relevant relationships through all levels of detail. The IDEF0 schemes appeared to be very useful in making a project breakdown in such a way that different aspects of the model could be assigned to different project team members to be worked out, without losing compatibility.

In modelling the system one of the most difficult aspects was the time-dependency of the relation between failure of the storm-surge barrier, the following water movements and the failure of the dikes surrounding the Eastern-Scheldt. Some significant simplifications had to be made in order to reduce the number of calculations. Again, IDEF0 proved to be helpful in assessing the effect of each simplification on the over-all model.

There is still a lot to be done though. Some of the most important further steps are mentioned in the next chapter.

5 FURTHER STEPS

At this stage the system description and model design have been made. In building a computerised SMS, the following steps have to be made:

– Making test calculations to check simplifications.
– Choosing the proper MC simulation technique.
– Building a pilot model. This is a “quick prototype” of the model in which the most important relations

are defined. The input numbers, however, are not revised.
– Testing the pilot model.

After testing the pilot model, we can decide whether or not the pilot model should be upgraded to a fully operational SMS model. In case it should, some of the input information and simplifications should possibly be reconsidered. This implies that the probability of failure of the storm-surge barrier should be calculated with the most recent information. In the end, the SMS model should be linked with maintenance models of both the storm-surge barrier and dikes in order to optimise the maintenance strategy for the whole flood defence system.

With the results presented in this paper a first step has been made in reaching that objective.

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